Nuclear correction factors from neutrino DIS

K. Kovařík

Institute for Theoretical Physics, Karlsruhe Institute of Technology, Karlsruhe, D-76128,Germany

Abstract. Neutrino Deep Inelastic Scattering (DIS) on nuclei is an essential process to constrain the strange quark parton distribution functions (PDF) in the proton. The critical component on the way to using the neutrino DIS data in a proton PDF analysis is understanding the nuclear effects in parton distribution functions. We parametrize these effects by nuclear parton distribution functions (NPDF) and we use this framework to analyze the consistency of neutrino DIS data with other nuclear data.

INTRODUCTION

Any prediction for a process measured at a hadron collider such as the LHC, involves necessarily parton distribution functions (PDFs). Because of how crucial the knowledge of PDFs is, there are many groups that perform and update global analyses of PDFs protons [1, 2, 3] and nuclei [4, 5]. Although not often emphasized, nuclear effects are present also in the proton PDFs analysis as a number of experimental data is taken on nuclear targets. Mostly though, the nuclear targets used in the proton analysis, are made of light nuclei where nuclear effects are generally small. An important exception is the neutrino DIS data which is taken on heavy nuclei such as iron or lead and is sensitive to the strange quark content of the proton. A knowledge of the strange quark PDF has an influence on precise measurements at the LHC such as W- or Z-boson production.

In order to include the neutrino DIS data in a global fit to determine proton PDF, we have to apply a nuclear correction factor. The nuclear correction factor can be obtained either from a specific model of nuclear interactions or from an analysis of nuclear parton distribution functions (NPDF) based on experimental data.

Here, we present a framework for a global analysis of nuclear PDFs at next-to-leading order in QCD closely related to the CTEQ framework for proton PDFs. We analyze and compare the nuclear correction factor obtained from the usual charged lepton DIS and Drell-Yan (DY) data to the one from the neutrino DIS data mainly from the NuTeV experiment.

NUCLEAR PDF

To determine parton distribution functions from experimental data, we parametrize the x-dependence of PDFs at an input scale Q_0 and use the DGLAP equations to change the scale of experimental data to Q_0 in order to perform a fit to the data. The global NPDF framework, we use to analyze charged lepton DIS and DY data and neutrino DIS

data, was introduced in [6]. The parameterizations of the nuclear parton distributions of partons in bound protons at the input scale of $Q_0 = 1.3\text{GeV}$

$$x f_k(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5} , \qquad (1)$$

where $k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$ and

$$\bar{d}(x, Q_0) / \bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4} , \qquad (2)$$

are a generalization of the parton parameterizations in free protons used in the CTEQ proton analysis [7]. To account for different nuclear targets, the coefficients c_k are made to be functions of the nucleon number A

$$c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} \left(1 - A^{-c_{k,2}}\right), \ k = \{1, \ldots, 5\}. \qquad (3)$$

The proton PDF in this framework are obtained as a limit $A \rightarrow 1$ and are held fixed at values obtained in the analysis [7]. From the input distributions, we can construct the PDFs for a general (A, Z)-nucleus

$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{(A-Z)}{A} f_i^{n/A}(x, Q), \qquad (4)$$

where we relate the distributions of a bound neutron, $f_i^{n/A}(x, Q)$, to those of a proton by isospin symmetry.

In the analysis, the same standard kinematic cuts $Q > 2\text{GeV}$ and $W > 3.5\text{GeV}$ were applied as in [7] and we obtain a fit with χ^2/dof of 0.946 to 708 data points with 32 free parameters (for further details see [6]).

The nuclear effects extracted in the form of NPDF are usually presented in the form of nuclear correction factors. We discuss two nuclear correction factors in the following where both are related either to the DIS structure function F_2 in the charged-current (CC) νA process

$$R_{CC}^\nu(F_2; x, Q^2) \simeq \frac{d^A + \bar{u}^A + \ldots}{d^{A,0} + \bar{u}^{A,0} + \ldots} , \qquad (5)$$

or to the DIS structure function F_2 in the neutral-current (NC) $l^\pm A$ process

$$R_{NC}^{e,\mu}(F_2; x, Q^2) \simeq \frac{[d^A + \bar{d}^A + \ldots] + 4[u^A + \bar{u}^A + \ldots]}{[d^{A,0} + \bar{d}^{A,0} + \ldots] + 4[u^{A,0} + \bar{u}^{A,0} + \ldots]} . \qquad (6)$$

The superscript '$0'$' stands for using the free nucleon PDFs $f_i^{p,n}(x, Q)$ in Eq. (4).

In Fig. 1 (solid line), we show how the result of our global analysis of charged lepton data translates into these nuclear correction factors and how it compares with experimental data. As first observed in [8], the $R_{CC}^\nu(F_2; x, Q^2)$ correction factor calculated using Eq. 5 with parton densities from the fit to the charged lepton nuclear data, does not describe the NuTeV data well which raises the question if including neutrino DIS data in the global analysis corrects this behavior without spoiling the $R_{NC}^{e,\mu}(F_2; x, Q^2)$ correction factor which fits the charged lepton DIS and DY data well.

TABLE 1. Summary table of a family of compromise fits.

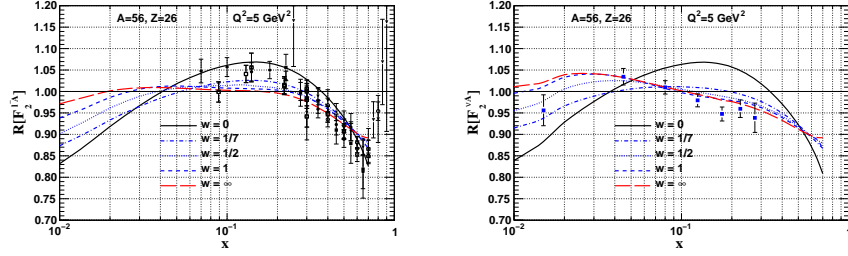| w	$\chi^2_{l^\pm A}$ (/pt)	$\chi^2_{\nu A}$ (/pt)	total χ^2(/pt)
0	638 (0.90)	-	638 (0.90)
1/7	645 (0.91)	4710 (1.50)	5355 (1.39)
1/2	680 (0.96)	4405 (1.40)	5085 (1.32)
1	736 (1.04)	4277 (1.36)	5014 (1.30)
∞	-	4192 (1.33)	4192 (1.33)

FIGURE 1. Nuclear correction factors $R^{e,\mu}_{NC}(F_2;x,Q^2)$ (left) and $R^{e,\mu}_{CC}(F_2;x,Q^2)$ (right) for compromise fits with different weights of the neutrino DIS data at the scale $Q^2 = 5\mathrm{GeV}^2$.

NEUTRINO DIS

In order to analyze the apparent discrepancy between the nuclear correction factor $R^\nu_{CC}(F_2;x,Q^2)$ from the fit to charged lepton data and the neutrino charged current DIS data, we have set up a global analysis where we used exclusively the neutrino DIS cross-section data coming from NuTeV and Chorus experiments taken on iron and lead respectively. Here we applied the same kinematic cuts as in the first analysis of the charged lepton data and we obtain a fit to 3134 neutrino DIS cross-section data points with χ^2/dof of 1.33 with 34 free parameters (for further details see [9]). A global fit to neutrino DIS data describes the data for the charged current nuclear correction factor $R^\nu_{CC}(F_2;x,Q^2)$ well and does a poor job to describe the neutral current correction factor especially at low and intermediate Bjorken x. In order to find nuclear correction factors in agreement with both charged lepton and neutrino data, we perform a combined global analysis of both data sets. We introduce an additional parameter in our analysis, the weight of the neutrino data set w, which should prevent the neutrino DIS data set to dominate the global fit based only on the number of data points taken. The weight w enters the calculation of the combined χ^2 as

$$\chi^2 = \sum_{l^\pm A \ \mathrm{data}} \chi^2_i + \sum_{\nu A \ \mathrm{data}} w\,\chi^2_i \,, \tag{7}$$

and it can be used to interpolate between the two different global fits ($w = 0$ results in the fit to charged lepton data only and $w = \infty$ stands symbolically for the fit only to neutrino data). Varying the weight w, we try to find a compromise fit which would describe both

charged lepton and neutrino data well. We list the resulting χ^2 for the compromise fits with weights $w = 0, 1/7, 1/2, 1, \infty$ in Tab. 1 and we show the nuclear correction factors $R_{NC}^{e,\mu}(F_2; x, Q^2)$ and $R_{CC}^{\nu}(F_2; x, Q^2)$ for the same family of compromise fits in Fig. 1.

In order to decide on how well the compromise fits describe the data we use the χ^2 goodness-of-fit criterion used in [10, 2]. We consider a fit a good compromise if its χ^2 for both data subsets, the charged lepton DIS and DY data and the neutrino DIS data, is within 90% confidence level of the fits to only charged lepton or neutrino data.

We define the 90% percentile ξ_{90} used to define the 90% confidence level, by

$$\int_0^{\xi_{90}} P(\chi^2, N) d\chi^2 = 0.90,\tag{8}$$

where N is the number of degrees of freedom and $P(\chi^2, N) = \frac{(\chi^2)^{N/2-1}e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$ is the probability distribution. We can assign a 90% confidence level error band to the χ^2 of the fits to the charged lepton DIS and DY data and to the neutrino DIS data

$$\chi_{l^{\pm}A}^2 = 638 + 45.6, \qquad \chi_{\nu A}^2 = 4192 + 138.\tag{9}$$

Comparing the results of the compromise fits with different weights, listed in Tab. 1, we see that none of the compromise fits are compatible with both 90% confidence level limits given in Eq.9. As detailed in [9], not even relaxing the condition to compare against the 99% confidence level limit helps to finding a suitable compromise fit. Moreover, we show in [9] that the effect is related to the precise neutrino DIS data from NuTeV.

CONCLUSION

After performing a thorough global NPDF analysis of the combined charged lepton and neutrino data, we find that there is no good compromise description of both the data sets simultaneously. The differences are most pronounced in the low and intermediate x regions where the neutrino DIS (NuTeV) do not show a strong shadowing effect as the charged lepton data do. The inability to describe all data by one consistent framework indicates the existence of non-universal nuclear effects or unexpectedly large higher-twist effects.

REFERENCES

1. R. D. Ball, et al., *Nucl. Phys.* **B823**, 195–233 (2009), 0906.1958.
2. A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, *Eur. Phys. J.* **C63**, 189–285 (2009), 0901.0002.
3. P. M. Nadolsky, et al., *Phys. Rev.* **D78**, 013004 (2008), 0802.0007.
4. M. Hirai, S. Kumano, and T. H. Nagai, *Phys. Rev.* **C76**, 065207 (2007), 0709.3038.
5. K. J. Eskola, H. Paukkunen, and C. A. Salgado, *JHEP* **04**, 065 (2009), 0902.4154.
6. I. Schienbein, et al., *Phys. Rev.* **D80**, 094004 (2009), 0907.2357.
7. J. Pumplin, et al., *JHEP* **07**, 012 (2002), hep-ph/0201195.
8. I. Schienbein, et al., *Phys. Rev.* **D77**, 054013 (2008), 0710.4897.
9. K. Kovařík, et al., *Phys.Rev.Lett.* **106**, 122301 (2010), 1012.0286.
10. D. Stump, et al., *Phys. Rev.* **D65**, 014012 (2001), hep-ph/0101051.